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Pulsar Spin-Down Induced Phenomena: Heating; Magnetic Field Evolution; Glitches; Pulse-Period Modulations

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Abstract. Modeling the dynamics of the quantum fluids within a spinning-down neutron star gives a description consistent with observed pulsar magnetic field evolution and spin-period "glitches." The long-standing problem of large predicted excesses in spin-down sustained pulsar heating from such models now seems resolvable. However, the origin of some pulsar spin-period and pulse-shape modulations which have been interpreted as manifestations of very long period ($\sim$ year) stellar precession is a crucial challenge to canonical neutron star models.

1. Introduction

In a cool core below the crust of a spinning neutron star (NS) superconducting protons coexist with the more abundant superfluid neutrons to form a giant atomic nucleus which includes a neutralizing sea of relativistic degenerate electrons. The neutrons rotate with a spin-period P (sec) only by forming a nearly uniform array of corotating quantized vortex lines parallel to the spin axis, with an area density $n_v \sim 10^4 \mathrm{cm}^{-2} P^{-1}$. The array contracts (expands) when the star spins-up (down). For stellar core neutron spin-up or spin-down, a vortex a distance $r_\perp$ from the spin axis generally moves with a velocity $\boldsymbol{v}_v = \boldsymbol{r}_\perp \dot{P}/2P$ until $r_\perp$ reaches the core neutron superfluid radius (R). Any stellar magnetic field passing below the stellar crust must, in order to penetrate through the superconducting protons, become bunched into a very dense array of quantized flux tubes ($n_\Phi \sim 5 \times 10^{18} B_{12} \mathrm{cm}^{-2}$ with B the local average magnetic field). Each tube carries a flux $2 \times 10^{-7} \mathrm{Gcm}^2$ and magnetic field $B_c \sim 3 \times 10^{15}$G. [This assumes a Type II proton superconductor below the crust, the result of essentially all calculations. If it were Type I, details would change but not the conclusions below.] The initial magnetic field within the core of a neutron star is expected to have both toroidal and very non-uniform poloidal components. The web of flux tubes formed after the transition to superconductivity is then much more complicated and irregular than the neutron vortex array as well as of order 10^{14} more dense.

Enough is understood about the dynamics of the components of a canonical NS to allow what should be a reliable, reasonably quantitative, description of what happens within a spinning magnetized NS as it ages and spins-down, and also in those rarer cases where it is spun-up by a companion. Because of the velocity dependence of the short range nuclear force between neutrons and protons

there is a strong interaction between the neutron superfluid's vortex lines and the proton superconductor's flux tubes if they come closer to each other than about 10^{-11}cm. Consequently, when $\dot{P} \neq 0$ flux tubes will be pushed (or pulled) by the moving neutron vortices [Sauls 1989, Srinivasan et al 1990, Ruderman 1991, Ding, Cheng, & Chau 1993, Ruderman, Zhu, & Chen 1998, Jahan-Miri 2000, Konenkov & Geppert 2001]. A realistic flux-tube array will be forced to move along with a changing neutron-superfluid vortex array which threads it as long as the force at a vortex-line flux-tube juncture does not grow so large that vortex lines cut through flux tubes. This is the basis for predicting an evolution of pulsar magnetic fields during spin-down or spin-up which seems to agree well with pulsar observaitons. However, it also leads directly to two crucial problems which could be "show stoppers" for modeling neutron star interiors if unresolved. We discuss the first of these next.

2. Heat Generation Inside Young Spinning-Down Pulsars

Just as in the case of a continuously disturbed magnetic field in a classical conducting fluid forced motion of a large flux tube array *through* the electron-proton sea in which it is imbedded could occur only if there is local ohmic dissipation. The main contribution to such dissipation is from the random part of electron scattering on the flux tube lattice [Ruderman et al. 1998]. If there is no flux-tube cutting so that all flux-tubes are pushed through a core's electron-proton sea, the heat production rate from it ($\dot{Q}$) has been calculated to be about 10^{35}erg s^{-1} within the $P = 0.9$ s Vela pulsar. A similar heating is predicted if there is flux tube cut-through in a Vela-like pulsar. But soft X-ray observations of the 10^4yr old Vela give a bound of $\dot{Q} < 10^{33}$erg s^{-1} [Ögelman, Finley, & Zimmerman 1993]. Therefore, a crucial question for all spin-down models of pulsars with strong interior magnetic fields is how moving core vortex lines move with, or through, the extraordinarily dense flux tube array in which they are imbedded without an unacceptably large $\dot{Q}$. (Special *ad hoc* magnetic field configurations which could greatly diminish $\dot{Q}$ appear implausible and also inconsistent with classical magnetohydrodynamical stability much earlier before cooling below the transitions to neutron superfluidity (vortices) and proton superconductivity (flux-tubes).) By far the most promising answer seems to be the huge drag reduction because of flux-tube clumping from the expected instability when flux-tubes are pushed by the somewhat flexible neutron superfluid vortex-lines. Vortex lines move a layer of flux-tubes as indicated in Fig. 1a. When the moving flux tubes, which repel each other strongly only at distances $\lesssim 10^{-11}$cm, form a "thick" blanket (Fig. 1b), their movement generates electron currents through the flux tube array which must be dissipated for the blanket to move through the $e - p$ fluid. Figure 1c is a side view of the vortex flux tube system in a reference frame where the vortex lines are at rest. The balance of forces between the force density from electron flow through flux tubes, the push of the vortex lines (the "Magnus force" which pushes them outward as the star spins-down), and the tension in the (bent) vortex lines, is exactly analogous to the pull of gravity ($\boldsymbol{g}$) in an upside down glass of water, the upward push of the atmosphere, and the surface tension at the water-air interface. Both systems are unstable in the same (Rayleigh-Taylor) way, and the interface instability quickly becomes large

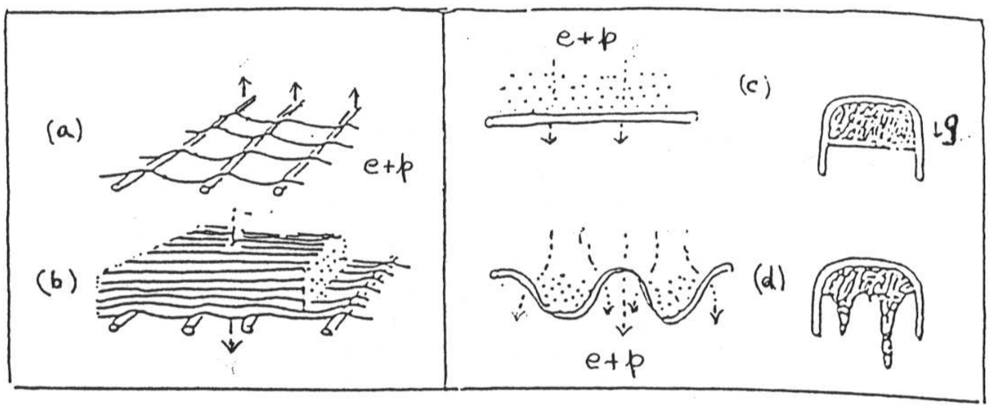

Figure 1. Flux-tube (lines) clumping by moving vortex lines (tubes).

and non-linear. Field-free spaces develop between clumps of flux tubes, through which unmagnetized $e-p$ fluid flows (Fig. 1d). Moving $e-p$ fluid in the vortex rest frame no longer passes through the flux-tube bundles. The resistance to the bunched flux tube flow in the $e-p$ rest frame is then only the viscosity of the unmagnetized degenerate electron sea around the bundles or, if the effective $e-e$ scattering mean free path of these electrons exceeds the radius of the flux tube bundles, the scattering of electrons by them. Preliminary numerical estimates for the scale of the instabilites and the drag on the moving bunches does indeed give a $\dot{Q}$ very much smaller than the upper bound allowed by the soft X-ray observations. Thus, except for possible constraints from the anchoring of the core's flux-tubes by the surrounding conducting crust, the expanding (contracting) neutron superfluid vortex array in the core of a spinning-down (up) pulsar should relatively easily induce a similar expansion (contraction) of the core's flux-tube array.

3. Surface Magnetic Fields of Spinning-Down Neutron Stars

The core of a cool neutron star is surrounded by a highly conducting 10^5cm thick crust which anchors any magnetic field through it until either the crust yield strength is exceeded by $\boldsymbol{j} \times \boldsymbol{B}$ forces in it and the most strongly magnetized parts of the crust follow the core flux tube movement below or eddy current decay allows crust flux movement. During various epochs in the life of a neutron star, this insures that its surface field will ultimately reflect that of the high flux density regions anchored at a crust's base. All of this leads to the evolutionary track shown in Fig. 2 for the surface dipole magnetic field of a pulsar as its period (P) changes. The "observed" NS's surface dipole field B is that inferred for the dipole moment $\boldsymbol{\mu}$ from $I\dot{\Omega} \simeq -\mu^2\Omega^3c^{-3}$. ($I$ is the NS moment of inertia.) The dipole evolutionary curve of Fig. 2 has the following segments.

Pulsar birth until a: B is constant. Core-vortex motion-induced field changes do not begin until the NS cools enough for both flux-tube and vortex-line formation. For $B \sim 3 \cdot 10^{12}$G, P will have grown to $P_0 \sim 20$ms before the

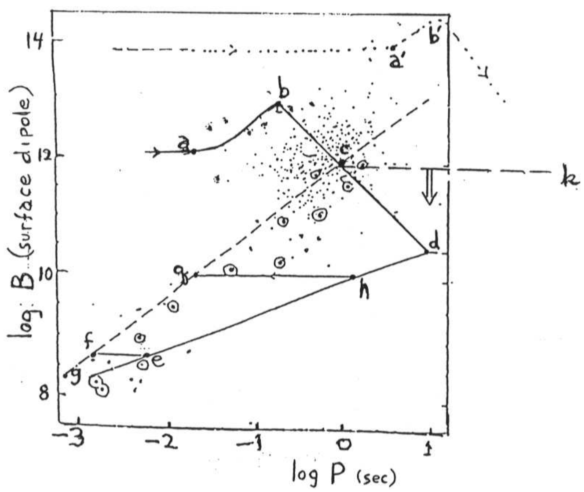

Figure 2. Model evolution of magnetic dipole field and observed values inferred from spin-down rates and periods of radio-pulsars. Starlike designations correspond to very young radio-pulsars in SNR's. Circled points are pulsars in binaries, usually spun-up candidates. The dashed line is the accretion-determined "spin-up line." The dotted line is for magnetar evolution.

required cooling is achieved no matter how much smaller the initial P may have been. (For a "magnetar" with $B \sim 10^{15}$G, $P_0 \sim 7$s.)

$a \rightarrow b$: Here $r_\perp \propto P^{1/2}$ until $r_\perp$ reaches the stellar radius R. The predicted evolution of $|\boldsymbol{\mu} \times \hat{\boldsymbol{\Omega}}| \equiv \mu_\perp$ is then particularly simple. Models which attribute spin-down mainly to the Maxwell torque, $I\dot{\Omega} \sim \mu_\perp^2 \Omega^3 c^{-3}$ have a "spin-down index" $n \equiv -\Omega\ddot{\Omega}\dot{\Omega}^{-2} = 3 - \frac{2\dot{\mu}_\perp \Omega}{\mu_\perp \dot{\Omega}}$. Because $\mu_\perp$ grows larger with increasing P, n grows from 2 to 3 until much of the surface flux is pushed out to $r_\perp \sim R$. These predicted n values compare reasonably with those observed in young high spin radiopulsars with measured n (Crab, $n = 2.5$ [Lyne, Pritchard, & Smith 1998]; PSR 1509-58, $n = 2.8$ [Kaspi et al. 1994]; PSR 0540, $n = 1.8$ [Zhang et al 2001]; PSR J1119, $n = 2.9$ [Camilo et al. 2000]).

$b \rightarrow c$: As flux tubes are pushed out of the core by the expanding vortex array, surface North and South poles are, at last, able to respond to the great pull of the large flux pushed into the lower crust and move to give surface field reconnection. Thereafter $|\mu_\perp|$ decreases roughly as P^{-1} (i.e.,$n = 5$), but the n at a particular P for any one pulsar cannot be predicted without a detailed *a priori* knowledge of its magnetic field structure[1]. The absence of many observed

[1] The Vela pulsar's suggested $n \sim 1.4$ [Lyne et al. 1996] is not incompatible with this model. Depending upon the original distribution of the core flux-tubes pushed to the crust-core interface by Vela's expanding vortex array, the movement of a North-South polar cap pair which ultimately reconnects may be either along a shortest connecting path (decreasing dipole and $n > 3$) or along a maximum length great circle path (first an increasing dipole so that $n < 3$, followed later by a decreasing one with $n > 5$ until the initial polar caps finally overlap). Al-

canonical pulsars with $P > P(\text{Vela}) = 0.9\text{s}$ but $B \geq B(\text{Vela}) \sim 3 \cdot 10^{12}\text{G}$, compared to a plethora of those with lower B, gives considerable support to the model prediction of a dipole B which now no longer grows with increasing P but decreases as shown in Fig. 2. Especially supportive is the reported factor of two difference between observed kinematic and spin-down pulsar ages, which corresponds exactly to the predicted for $n = 5$ [Cordes 2000].

$c \rightarrow k$ *and* $c \rightarrow d$: The point c is about where the maximum expected magnetic stress in the crust no longer exceeds the crust's yield strength. The evolution of surface B from further spin-down beyond c depends on time scales. The core surface B should follow the trajectory $c) \rightarrow d)$. The crust surface field would now follow it only when spin-down is slow enough for crustal eddy current dissipation or plastic creep ($P/\dot{P} >$ several $\times\, 10^6$yrs). On shorter time scales the crust surface field remains frozen at the value it had at the point c and the $c) \leftrightarrow k)$ segment could be followed during spin-down and spin-up of X-ray pulsars in accreting binaries. When these neutron stars become sufficiently old, however, their surface dipoles would drop to the $c \leftrightarrow d$ segment.

$d \rightarrow h \rightarrow q$, $d \rightarrow e \rightarrow f$, $d \rightarrow e \rightarrow g$: Here a dead radiopulsar in a low mass X-ray binary (LMXB) is assumed to be spun-up by accretion from its companion so that magnetic flux is now squeezed inward toward the spin axis. The superfluid vortex velocity within a neutron star being spun-up to a millisecond period in an LMXB, ($\sim 10^{-9}$ cm s^{-1}) is so small that a core flux tube motion which follows it seems inescapable even if there were no flux-tube bunching. None of the expectations for magnetic field evolution of NS's in such LMXBs are in conflict with observations. This includes a remarkably large fraction of apparently orthogonal and also of nearly aligned rotators among the disk population's fastest spinning millisecond pulsars (MSP's) [Chen, Ruderman, & Zhu 1998, Jayawardhana & Grindlay 1996]. Especially supportive is the magnetic field structure of PSR 1937+21 implied by its observed polarization properties and their radio frequency dependence [Chen & Ruderman 1993]. It is just that expected for the fastest spun-up MSPs ($P = 1.6$ms). Recycled case ($d \rightarrow b$) pulsars should reach the Fig. 2 spin-up line with a much more nearly canonical dipole field strength than that of most MSP's. At least one such radiopulsar in a binary seems to have been identified [Van den heuvel & Bitznaraki 1995]. Just below the spin-up line near it is also where most candidates for nearly aligned pulsars (i.e. radiopulsars with anomalously broad pulse-widths) are found, as expected from this evolutionary model). Very strong support for the "squeezed flux" MSP model also comes from the thermal part of the X-ray emission expected from the polar cap of the nearly aligned MSP PSR 0437. It has been reported at this meeting [Trümper 2001] to be from a surface hot spot about 10^{-2} the size of a canonical (i.e., central dipole or uniformly magnetized NS) polar cap with the PSR 0437 spin-period. This is just what has been predicted for the "squeezed flux" spin-up model for that pulsar [Chen et al. 1998].

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ternatively the surface field may begin with many North and South polar caps. The net dipole moment is then the resultant of several dipoles. One of these could become smaller but the resultant increase. Only after relatively long evolution is $\langle n \rangle \sim 5$ realized. (Vela's presently increasing dipole moment may occur mainly in sudden crust cracking events ("glitches", cf §4)).

4. Glitches in Canonical Pulsar Spin-Periods

The expansion of a core vortex array in a spinning-down pulsar would overstress the crust in two ways. First, outward moving vortices pull on the crust through the crust anchored flux-tubes which they pull with them. The crust could "crack" from the resulting overstrain in both the $a \to b$ and the $b \to c$ segments of Fig. 2. Each maximum crust displacement would be expected [Ruderman 1991, et al. 1998] to give a $\Delta\mu_\perp/\mu_\perp \sim +10^{-3\pm1}(3-n)^{-1}$. This is consistent in sign and magnitude with the larger observed unhealed jumps $\Delta\dot{P}/\dot{P} \sim 5 \times 10^{-4}$ in the family of weak Crab pulsar period glitches [Lyne, Smith, & Pritchard 1992]. These are by far the largest observed non-transient fractional changes in any pulsar parameters after a glitch. (It is not yet known if similar jumps occur in larger glitches of other pulsars.) Such crust movement can cause small jumps in the crust spin-rate in two ways: (1) Crust-lattice pinned vortices may be shaken loose. While this may no longer seem large enough to give the giant Vela-like glitches [Jones 1998] it may still suffice for the much smaller Crab-like ones. (2) A new but necessary contribution is from the reduction in pull-back on the outwardly moving *core* vortex lines by the moved crust's pinning of core flux tubes. The core vortices must adjust to it by an (non-instantaneous) outward displacement. This alone has been crudely estimated to give a crust glitch frequency jump with a magnitude similar to those of the Crab ones if the proposed reduction of $\dot{Q}$ by reduced flux tube drag is valid. A second family, the *giant* Vela-like glitches would come from a different kind of sudden core vortex movement. In the absence of a very dense flux tube environment, outward moving core vortices would smoothly shorten and then disappear as they reached the core's equator (Fig. 3. right hemisphere). However, the highly conducting crust strongly resists entry by the flux array which moves with these vortices (Fig. 3 left hemisphere). This pile-up of pushed flux tubes in an equatorial annulus also prevents vortex line expulsion into the lower crust and disappearance there until either vortex-line flux-tube cut-through events or a sudden "cracking" of overstressed crust which allows field adjustments. Until either begins the superfluid in the annulus rotates with period $P_0(\ll P)$ since none of the vortices which formed when the entire core had the period P_0 have yet been able to leave the core. Giant Vela-like glitches are proposed as the events which allow a sudden reduction of this annulus of excess angular momentum by outward movement of these trapped vortices when the crust finally yields to the magnetic stress at its base. These would be expected along the $b \to c$ segment in Fig. 2, where reconnection begins ($\bar{n} \sim 5$), but before point c is reached where crust strength prevents further cracking. This is indeed the segment on which giant glitches have so far been observed. The time scale between such glitches should be related to the cracking displacement (d). If this is about the same as that in the larger Crab glitches, $d \sim (\Delta\mu_\perp/\mu_\perp)\, R \sim 3 \cdot 10^{-4}R$, there would then be $\sim R/d \sim 3 \cdot 10^3$ giant glitches during Vela's spin-down age or about one each three years. This is encouragingly close to that observed but details must be worked out.

This model for the two families of pulsar spin-period glitches attirbutes both mainly to phenomena involving spin-down of *core* neutron superfluid. It differs from the presently most widely applied models for radiopular spin-up "glitches" which assume glitches to be caused by a sudden reduction in rotation speed

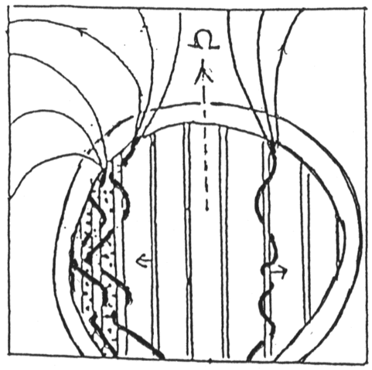

Figure 3. RHS. Vortices move outward and disappear smoothly at the core equator. LHS: Vortices squeeze flux tube array against the highly conducting crust which keeps them from reaching the equator. In that outer annulus neutron superfluid retains its initial period (P_0).

of the crust's neutron superfluid filling the space between the crustal lattice nuclei. That crust superfluid is assumed to be prevented from spinning-down with the rest of the star because of pinning of its vortices to those nuclei [Alpar et al 1984, 1993]. A glitch is supposed to be caused by a sudden collective unpinning. However, there appear to be significant unresolved problems with this kind of glitch model. a) The most compelling is from work of Jones [1998], who calculated the propagation of vortex unpinning in a crust. He finds that this occurs typically two (or more) orders of magnitude too easily to allow enough pinning for unpinning events to give the observed "giant glitches" in the Vela pulsar spin rate ($\Delta P/P \sim -$several $\times 10^{-6}$ at intervals $\tau_g \sim 3$yr). He concludes: "glitches do not originate in the crust" (cf, however, Link and Cutler [2001]). b) Glitches are observed in two rather separate groups: giant Vela-like glitches (upper arrow in Fig. 4) and a separate family with glitches about 10^{-2} as large [lower arrow in Fig. 4]. Individual pulsars on the $\overline{bc}$ segment of Fig. 2. may have both kinds. Perhaps even more significant, giant Vela glitches seem to begin with much larger initial spin-frequency jumps which quickly relax [McCulloch et al. 1990, Lundgren 1995] to those of Fig. 4, while the only Crab glitch observed from its beginning (only 10^{-2} as large as the Vela ones) shows quite the opposite initial behavior. This dichotomy has not been easily explained in crustal vortex unpinning models. By comparison, the existence of two separate glitch families with about the observed $\Delta P/P$ and early time evolutionary differences are consequences of the magnetic field evolution model of §3 if we add to it the common assumption that crustal stresses which grow to exceed significantly the crust's yield strength are relieved by sudden (less than 10^2s) crust displacements ("cracks" or "starquakes").

Up to this point the above description of pulsar evolution — based upon expected vortex, flux-tube, and crust dynamics — appears to do well in its confrontations with pulsar observations. However, there is one family of recent observations which seems to present an extremely embarassing problem for it, and we turn next to that question.

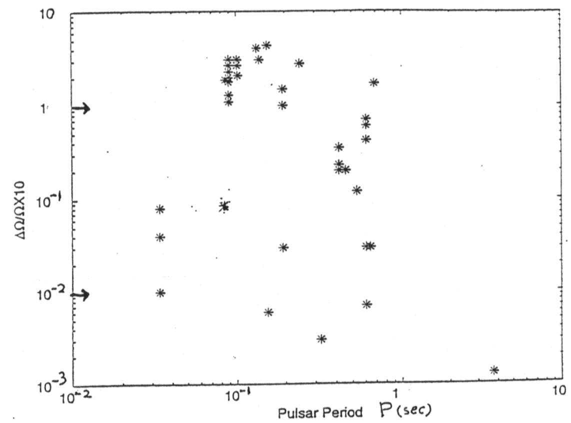

Figure 4. Pulsar glitch magnitudes ($\Delta\Omega/\Omega\times10^6$) in various spinning-down pulsars. Data from Lyne [1995].

5. Long Period Free Precesison in Some Radiopulsars?

Year-period non-sinusoidal oscillations observed in some radiopulsar pulse shapes, $\dot{P}$, and P have been interpreted as NS free precession [Stairs, Lyne, & Shemar 2000, Cordes 1993, Lyne et al. 2001] (or at least that of the conducting crust in which the surface $\boldsymbol{B}$-field is fixed) because it seemed the only plausible explanation. But this gives rise to a paradox: because of the interaction between the solid crust's nuclei and its internuclear superfluid neutrons' vortex lines, crustal precession should have periods or damping times orders of magnitude smaller than a year [Shaham 1977, Sedrakian, Wasserman, & cordes 1999, Link & Epstein 2000]. The strong interaction between the *core's* vortices and flux tubes, together with the crustal pinning of core magnetic field when it passes through the crust, makes this already too short time scale even smaller and more difficult to evade. This is a crucial problem which will raise doubts about canonical descriptions of NS structure until it is solved[2].

[2]With this in mind A possible but very different interpretation of this "precession" may be that the observed radiopulse structure oscillations are not caused by precession of the NS but only that of parts of its magnetospheric current pattern which slowly rotates relative to the NS external magnetic field. Such a motion has already been suggested [Ruderman & Sutherland 1975] as the origin of the well known radiopulsar "drifting sub-pulse" phenomenon [Backer 1973, Desphande & Rankin 1999]: $\boldsymbol{v} = \boldsymbol{E}\times\boldsymbol{B}c/B^2$ drift inside a radiopulsar's polar cap (PC) accelerator gives the $e^{\pm}$ outflow above the accelerator and the currents within it an additional spin $\boldsymbol{\Omega}_d \sim \Delta V\Phi^{-1}\hat{\boldsymbol{B}} \sim 10\hat{\boldsymbol{B}}\mathrm{s}^{-1}$. ($\Phi$ is the open field line flux through the PC accelerator and $\Delta V(\sim 10^{12}V)$ is the potential drop through it.) With non-axisymmetric surface fields and gravitaitonal bending of PC initiated γ-rays, or possibly γ-rays produced from "outergap" accelerators, $e^{\pm}$ associated current flows can exist on open $\boldsymbol{B}$-field lines which do not pass through a PC accelerator before reaching the NS surface. These will, however, need a distributed $e\Delta V \sim mc^2$ along their flow to adjust the local net charge density to that needed to keep $\boldsymbol{E}\cdot\hat{\boldsymbol{B}} \sim 0$. For such flows $\Omega_d \sim mc^3/e\Phi \sim 2\pi\mathrm{yr}^{-1}$ near the needed "precession" rate. (There remains the hard long stnading question of the deveopment of non-uniform current

6. An Acknowledgement

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